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Density oscillations in systems of colliding heavy ions observed via hard-photon interferometry measurements ★

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Abstract

We have analyzed hard-photon intensity correlations measured in the systems ^{86}Kr+^{nat}Ni at 60.0*A* MeV and ^{181}Ta+^{197}Au at 39.5*A* MeV assuming that hard photons are emitted from two distinct sources in space-time. We confirm the existence of the Bose-Einstein correlation between independent hard photons and attribute the origin of the two sources to the density oscillations of nuclear matter generated in intermediate-energy heavy-ion collisions via the incomplete-fusion reaction mechanism.

In the preceding Letter [1] we have shown that BUU calculations predict that within the energy regime where heavy-ion collisions lead to a density oscillation and form a hot nucleus through the incomplete-fusion mechanism [2], hard photons ($E_\gamma > 30$ MeV) originate from two sources distinct in space and time. In the initial stage, *direct* hard photons originate from a dense source during the first compression-phase and constitute the dominant contribution, while in a later stage the *thermal* hard photons originate from a thermalized source during

★ Experiments performed with TAPS at the GANIL facility, Caen, France.

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ulterior compression-phases. The first experimental evidence for the existence of these two photon sources has been found in the photon energy-spectra measured with TAPS and presented in the preceding Letter [1]. A more powerful tool to characterize the properties of the photon source is provided by two-photon inclusive measurements. In particular, two-photon relative momentum distributions will allow to determine directly the collision geometry using the technique of intensity interferometry between independent hard photons.

Recently we have reported on such a measurement [3] for the system ^{86}Kr+$^{\rm nat}$Ni at 60.0A MeV, in which for the first time the Bose-Einstein interference effect in intermediate-energy nuclear physics was observed in the two-photon correlation. We found in this study a space-time extent of the source surprisingly larger than the size of the system in the entrance channel. To solve this puzzle we have repeated a similar measurement for the much heavier system ^{181}Ta+^{197}Au at 39.5A MeV and we have analyzed both sets of data in terms of a two-source photon emission as suggested by the theoretical predictions. We find that the measured photon correlation functions can only be interpreted by assuming a photon emission from two distinct sources for which we have estimated the spatial extent and relative intensities. Bose-Einstein correlations force identical bosons to be emitted with smaller relative momenta than non-identical particles under otherwise similar conditions. This effect is a consequence of the symmetrization of the two-body wave function for identical bosons. The standard definition of the correlation function C_{12} as a function of the boson four-momenta p_i is

$$C_{12}(p_1,p_2) = \frac{P_2(p_1,p_2)}{P_1(p_1) \otimes P_1(p_2)}, \tag{1}$$

where P_2 is the two-boson coincidence yield, subject to Bose-Einstein symmetrization, and P_1 the single-boson yields. Since the interference term of C_{12} is related to the space-time boson-source density [4], the study of two-boson (photon) correlations gives access to information on the medium from which they are emitted.

Assuming that the space-time photon source can be parametrized by a normalized density distribution of the form $\rho(r) = \exp(-r^2/2R^2 - t^2/2\tau^2)$, the correlation function $C_{12}^{(1)}$ depends on the relative four-

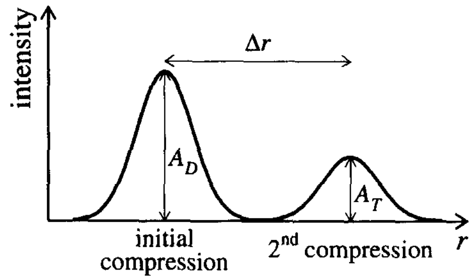

Fig. 1. Photon-source distribution in the space-time coordinate.

momentum q between the two photons via the Fourier transform of $\rho(r)$ [4]:

$$C_{12}^{(1)}(q) = 1 + \lambda\ \exp(-q^2R^2 - q_0^2\tau^2). \tag{2}$$

The parameter λ takes into account several characteristics [4] of the photon emission and the width of the interference pattern is a measure of the source extent. To study the effect of a secondary photon source displaced in space-time by the four-vector Δr, we have assumed that both sources have the same distribution $\rho(r)$ and we have called $A_{\rm D}$ the relative intensity of direct hard photons and $A_{\rm T} = 1 - A_{\rm D}$ the one of thermal hard photons, as shown in Fig. 1. It is straightforward to deduce the resulting correlation function $C_{12}^{(2)}$ replacing in Eq. (2) $\rho(r)$ by $A_{\rm D}\rho(r) + A_{\rm T}\rho(r - \Delta r)$:

$$C_{12}^{(2)}(q) = 1 + \lambda\ \exp(-q^2R^2 - q_0^2\tau^2)\ \mathcal{I}_{gg}(q), \tag{3}$$

$$\mathcal{I}_{gg}(q) = A_{\rm D}^2 + A_{\rm T}^2 + 2A_{\rm D}A_{\rm T}\cos(q\Delta r), \tag{4}$$

where the argument of the cosine is the four-vector product $q\Delta r = q_0\Delta t - \boldsymbol{q}\Delta\boldsymbol{r}$. The interference term of the correlation function in Eq. (3) is again given by the Fourier transform of $\rho(r)$ but modulated by the factor $\mathcal{I}_{gg}$ which depends on the relative intensities of the two sources and on their space-time separation. In the case of no density oscillation, i.e., one source, as would happen at bombarding energies high enough to break the system into fragments [1], $A_{\rm T} = 0$, $\mathcal{I}_{gg} = 1$ and Eq. (3) reduces to Eq. (2).

This analysis has been applied to the data measured for the system ^{86}Kr+$^{\rm nat}$Ni at 60.0A MeV. Hard-photon pairs were detected and identified with the photon spectrometer TAPS. The experimental conditions and the identification algorithms are described in [3]. The energy threshold to select hard photons was 25 MeV, which improves the statistics and keeps the contribution from GDR photons down to 5%. To compare the data for this light system with those for a heavier one, and to demonstrate the high sensitivity of the correlation technique to the characteristics of the photon source, we have performed a new experiment with exactly the same setup and have applied the same analysis. The system was ^{181}Ta+^{197}Au at 39.5A MeV, for which BUU calculations [1] predict a much higher thermal-photon production rate. The ^{181}Ta beam was delivered by the GANIL accelerators at an average intensity of 8 nAe. The gold target was 11.23 mg/cm^2 thick and rotated by 10° from the direction vertical to the beam axis. The total accumulated beam was 2.6×10^{14} particles. In both cases the correlation function was constructed, according to Eq. (1), as the ratio between the two-photon coincidence yield and the uncorrelated background generated by folding the single-photon yields. The method to normalize the correlation function in the region where the correlation effects (Bose-Einstein and π^0 decay) vanish is described in [3]. In the same reference we justify the use of the Lorentz-invariant relative four-momentum $Q = (\boldsymbol{q}^2 - q_0^2)^{1/2}$ as the most appropriate variable to construct a one-dimensional correlation function, since the general relation between the relative energy and the relative three-momentum ($q_0 \leq |\boldsymbol{q}|$) is much more restrictive in our case: $q_0 \ll |\boldsymbol{q}|$. This is due on the one hand to the exponential shape of the photon energy (and thus of q_0) spectrum, which leads to an average q_0 value close to zero. On the other hand the large angular coverage of our setup allows to measure almost the total $|\boldsymbol{q}|$ distribution as the opening angle between both photons ranges from 18° up to 180°. We then write the correlation function as

$$\begin{aligned} C_{12}(\boldsymbol{q}, q_0) &\equiv C_{12}(Q) \\ &= 1 + \lambda\ \exp(-Q^2 R_Q^2) \\ &\times [A_D^2 + A_T^2 + 2A_D A_T \cos(Q\Delta)]. \end{aligned} \tag{5}$$

Using Monte Carlo simulations we have found that this correlation function is equivalent to the one of Eq. (3). In the above relation, R_Q is the space-time parameter conjugate to Q which measures an invariant length but not exactly the source extent. As shown in [5,6], the general relation between R_Q, R and τ is

$$R_Q = R\sqrt{\frac{1 + (\tau/R)^2(q_0/|\boldsymbol{q}|)^2}{1 - (q_0/|\boldsymbol{q}|)^2}}. \tag{6}$$

One can easily see that the fact that $q_0 \ll |\boldsymbol{q}|$ makes R_Q almost insensitive to τ (it affects mainly λ [6]) and provides at first-order a measure of the spatial source extent $R \approx R_Q$. Within this approximation the root-mean-square radius of the source can be calculated as the one of a static three-dimensional Gaussian source: $R_{\rm rms} = \sqrt{3}R_Q$. In this analysis, Δ should be considered as a *fitting parameter* which we can interpret only qualitatively. It is somehow related to the spatial and temporal separation between the two sources, i.e., to the reaction dynamics, but it might also contain some additional effects like, e.g., differences between the actual density distribution of the source and the assumed distribution in Fig. 1.

In Fig. 2 we show the experimental correlation functions (open squares) measured for both systems. We describe the π^0 contribution by an asymmetric Gaussian function and verify that it is negligible in the region $Q < 60$ MeV [3,6]. While for the lighter system the correlation function exhibits at small Q a clear Gaussian-like pattern, which in [3] was attributed to a large photon source, in the heavier one we do not observe any Gaussian-like pattern. We therefore conclude that Eq. (2), which assumes one space-time source cannot represent the experimental correlation functions.

We have then fitted Eq. (5) to the data with λ, R_Q, A_D and Δ as free parameters. The fitted parameters are listed in Table 1. The result is shown in Fig. 2 by the solid line together with the two contributions plotted separately: the Gaussian one by the dashed line and $\mathcal{I}_{gg}$ by the dotted line. We observe that the assumption that hard photons are emitted from two distinct sources leads to an excellent agreement with the data. The effect of the second source is to attenuate for the light system the Gaussian pattern expected in the correlation function (dashed line in Fig. 2) and to completely wash out the pattern for the heavy system where the intensities of both sources are equal. The value deduced for R_Q leads to a source size of $R_{\rm rms}^{\rm KrNi} = (5.7 \pm 1.6)$ fm and $R_{\rm rms}^{\rm TaAu} = (7.8 \pm 2.6)$ fm, which according to Eq. (6) should be considered as upper limits. These source sizes follow the size of the compound system, $R_{\rm rms}^{\rm KrNi}/R_{\rm rms}^{\rm TaAu} = (1.4 \pm 0.6)$ and $R_{\rm (Kr+Ni)}/R_{\rm (Ta+Au)} = 1.38$, demonstrating that the observed effect is related to the size of the colliding heavy ions. The values deduced from the fit for the relative intensity of direct hard photons are $(79 \pm 10)\%$

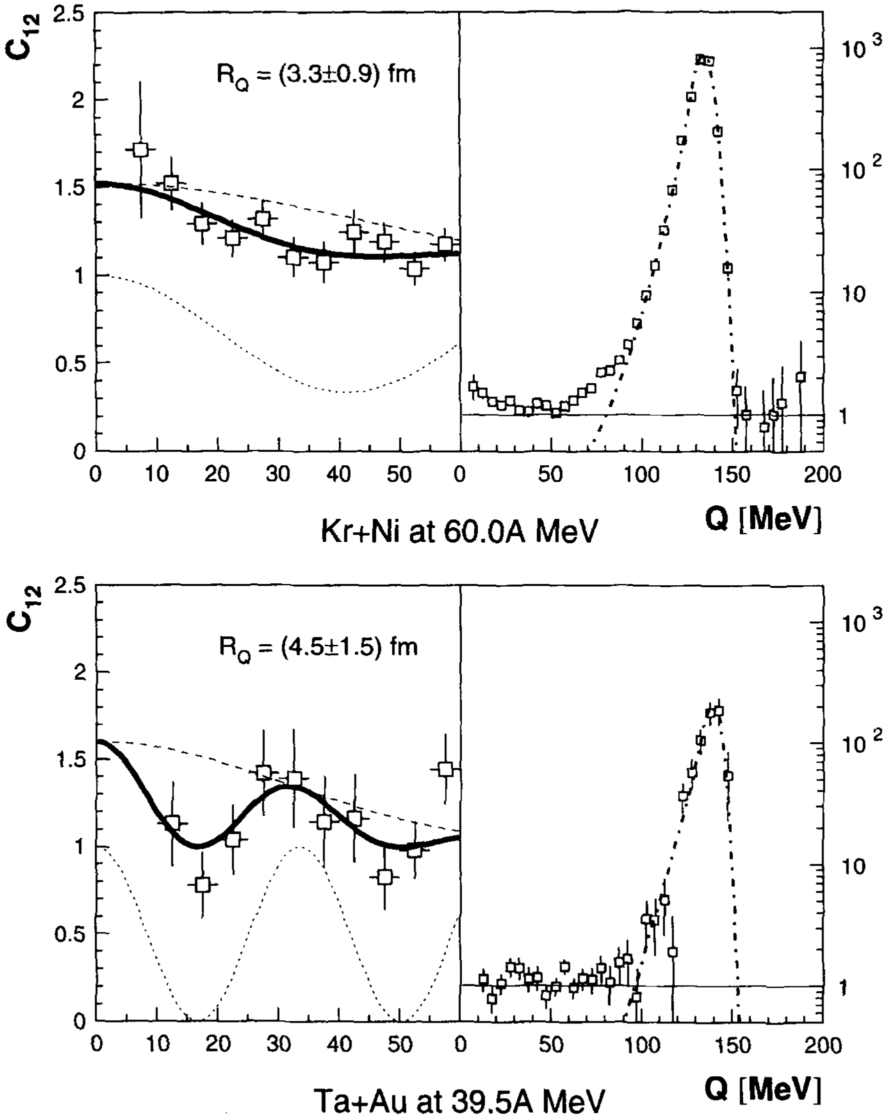

Fig. 2. Correlation function measured for the systems ^{86}Kr+^{nat}Ni at 60.0A MeV and ^{181}Ta+^{197}Au at 39.5A MeV. On the left, the full line represents the fit of Eq. (5) to the data, decomposed in the case of one unique source (dashed line) and the factor between brackets (dotted line). The resulting parameters are shown in Table 1. On the right, the dot-dashed line represents the asymmetric Gaussian function describing the π^0 contribution to the correlation function [3,6].

Table 1
Parameters deduced from the fit of Eq. (5) to the data shown in Fig. 2

System	E [MeV]	λ	R_Q [fm]	A_D [%]	Δ [fm]
Kr+Ni	60.0A	0.52±0.17	3.3±0.9	79±10	15±3
Ta+Au	39.5A	0.6 ±0.3	4.5±1.5	50±16	37±3

for Kr+Ni and $(50 \pm 16)\%$ for Ta+Au. BUU calculations described in the preceding Letter [1] were performed for $E_\gamma > 25$ MeV at an average impact parameter given by a geometrical model [7] for collisions producing two hard photons. The relative intensity A_D predicted was 74% of the total photon yield for Kr+Ni and 58% for Ta+Au, in excellent agreement with the values deduced from the fit to the experimental correlation function. Finally, the values obtained for the parameter Δ seem closer to an estimate of the spatial separation ($\beta_{AA}\Delta t \approx 20$ fm, where β_{AA} is the nucleus–nucleus center-of-mass velocity) than to the temporal one ($\Delta t \approx 100$ fm/c), but since our analysis does not allow to map out the full six-dimensional two-particle space and we do not know the details of the reaction dynamics, we cannot give a quantitative description of Δ nor interpret the difference between the values obtained for the two systems.

In conclusion, we have shown that the hard-photon correlation function measured for two systems very different in size and bombarding energy cannot be interpreted with the assumption of a single photon source. By introducing a second photon source we obtain a good description of the data. This observation is in agreement with the reaction mechanism expected for heavy-ion collisions at low-intermediate bombarding energies leading to the formation of a hot nucleus oscillating in a monopole mode. It confirms also the prediction of the BUU calculation that bremsstrahlung photons are emitted during each compression phase. We have therefore at hand with hard photons a probe emitted at two very different stages of the collision, the initial one when nuclear matter is formed at high densities and the second one when nuclear matter reaches again high densities but is already thermalized. This result opens new opportunities to study the properties of hot and dense nuclear matter.

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